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Search for CP Violation in Charged D Meson Decays

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Abstract

We report results of a search for CP violation in the singly Cabibbo-suppressed decays $D^+ \to K^-K^+\pi^+$, $\phi\pi^+$, $\overline{K}^*(892)^0K^+$, and $\pi^-\pi^+\pi^+$ based on data from the charm hadroproduction experiment E791 at Fermilab. We search for a difference in the D^+ and D^- decay rates for each of the final states. No evidence for a difference is seen. The decay rate asymmetry parameters (A_{CP}), defined as the difference in the D^+ and D^- decay rates divided by the sum of the decay rates, are measured to be: $A_{CP}(KK\pi) = -0.014 \pm 0.029$, $A_{CP}(\phi\pi) = -0.028 \pm 0.036$, $A_{CP}(K^*(892)K) = -0.010 \pm 0.050$, and $A_{CP}(\pi\pi\pi) = -0.017 \pm 0.042$.

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CP violation can be accommodated in the Standard Model (SM) by a complex phase in the Cabibbo-Kobayashi-Maskawa matrix describing the transitions between quarks induced by the charged weak interaction. To date, CP violation has been observed only in the neutral kaon system. It is being actively searched for in B decays, where the effects of CP violation in the SM are expected to be large [1], and in hyperon decays [2]. In contrast to the strange and bottom sectors, the SM predictions of CP violation for charm decays are much smaller [3], making the charm sector a good place to test the SM and to look for evidence of physics beyond the SM [4].

CP violation occurs if the decay rate for a particle differs from its CP conjugate decay rate: $\Gamma(D \to f) \neq \Gamma(\overline{D} \to \overline{f})$. Such an asymmetry requires the interference of at least two independent amplitudes with non-zero relative phase. In D decays, as in K and B decays, there are two classes of CP violation: indirect and direct. In the case of indirect CP violation, the asymmetry is associated with mixing, which can occur only in neutral meson decays. In the case of direct CP violation, final state interactions must induce a strong phase shift and both the strong and weak phases of the two amplitudes must differ. This can occur in both charged and neutral meson decays. In the SM, direct CP-violation asymmetries in D decays are predicted to be largest in singly Cabibbo-suppressed (SCS) decays (at most of the order of 10^{-3}) and non-existent in Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) decays [3].

Current experimental sensitivity to decay rate asymmetries due to direct CP violation, defined below, is of the order of 10^{-1}. Experimental results on searches for CP violation in D^0 decays come from E691 [5], E687 [6], and CLEO [7]. However, limits on CP violation in D^+ decays come only from E687 [6]. In this letter, we report on a higher-statistics search for evidence of direct CP violation in the SCS decays $D^+ \to K^-K^+\pi^+$ (inclusive), $\phi\pi^+$, $\overline{K}^*(892)^0K^+$, and, for the first time, $\pi^-\pi^+\pi^+$.

The signature for CP violation in charged D decays is an asymmetry in the decay rates:

$$A_{CP} = \frac{\Gamma(D^+ \to f^+) - \Gamma(D^- \to f^-)}{\Gamma(D^+ \to f^+) + \Gamma(D^- \to f^-)}. \tag{1}$$

To the extent that

$$\frac{\epsilon(D^+ \to f^+_{SCS})}{\epsilon(D^- \to K^-\pi^+\pi^+)} = \frac{\epsilon(D^- \to f^-_{SCS})}{\epsilon(D^- \to K^+\pi^-\pi^-)}, \tag{2}$$

where ϵ is our detector efficiency and $f^{\pm}_{SCS}$ is $K^{\mp}K^{\pm}\pi^{\pm}$, $\phi\pi^{\pm}$, $K^*(892)K^{\pm}$, or $\pi^{\mp}\pi^{\pm}\pi^{\pm}$, we can normalize the production rates relative to the CF mode $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$. Then, Eq. (1) becomes

$$A_{CP} = \frac{\eta(D^+) - \eta(D^-)}{\eta(D^+) + \eta(D^-)}, \tag{3}$$

where

$$\eta(D^{\pm}) = \frac{N(D^{\pm} \to f^{\pm}_{SCS})}{N(D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm})} \tag{4}$$

and N is the number of observed D decays. Thus, differences in the $D^{\pm}$ production rates [8], relative efficiencies, and most other sources of systematic errors cancel.

E791 is a high statistics charm experiment which ran at Fermilab during the 1991-1992 fixed-target run. The experiment [9] combined an extremely fast data acquisition system with an open trigger to record the world's largest sample of open charm. Over 20 billion events were collected from a 500 GeV π^- beam interacting in five thin target foils (one platinum and four diamond), using the Tagged Photon Spectrometer. The spectrometer included 23 planes of silicon microstrip detectors (6 upstream and 17 downstream of the target), 2 dipole magnets, 10 planes of proportional wire chambers (8 upstream and 2 downstream of the target), 35 drift chamber planes, 2 multicell threshold Čerenkov counters that provided π/K separation in the 6–60 GeV/c momentum range [10], electromagnetic and hadronic calorimeters, and a muon detector.

All selection criteria (cuts) used to choose candidate SCS decays $D^{\pm} \to K^{\mp}K^{\pm}\pi^{\pm}$, $\phi\pi^{\pm}$, $K^*(892)K^{\pm}$, and $\pi^{\mp}\pi^{\pm}\pi^{\pm}$, with the exception of Čerenkov identification requirements, were optimized to maximize $S/\sqrt{S+B}$, where S is the number of CF $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ signal events, scaled to the level expected for each SCS decay mode, and B is the the number of background events for each of the signals studied. Decay vertices were required to be located outside the target foils, and the significance of separation from the primary vertex in the beam direction ($\Delta z/\sigma_{\Delta z}$) was required to be at least 11 for $KK\pi$, 8 for $\phi\pi$, 9 for K^*K, and 14 for $\pi\pi\pi$. The component of the D momentum perpendicular to the line joining the primary and secondary vertices was required to be less than 0.35 GeV/c for $KK\pi$, $\phi\pi$, and K^*K, and 0.20 GeV/c for $\pi\pi\pi$. The impact parameter of the D momentum with respect to the primary vertex was required to be less than 55 μm for $KK\pi$ and K^*K, 80 μm for $\phi\pi$, and 40 μm for $\pi\pi\pi$. Decay tracks were required to pass closer to the secondary than to the primary vertex and the sum of the square of their momenta, perpendicular to the D direction, was required to be larger than 0.30 (GeV/c)^2 for $KK\pi$, K^*K, and $\pi\pi\pi$, and 0.15 (GeV/c)^2 for $\phi\pi$.

In the decay $D^\pm \to K^\mp\pi^\pm\pi^\pm$, the kaon was identified on the basis of charge alone and no Čerenkov identification cuts were applied. Also, in the decay $D^\pm \to \phi\pi^\pm$, no Čerenkov identification cuts were applied due to the ϕ mass selection criteria. In the decays $D^\pm \to K^\mp K^\pm\pi^\pm$ and $K^*(892)K^\pm$, Čerenkov identification cuts improved the signal significance. In these decay modes, tracks considered as kaons were required to have kaon signatures in the Čerenkov counters. No Čerenkov identification cuts were applied for the decay $D^\pm \to \pi^\mp\pi^\pm\pi^\pm$. To minimize the systematic uncertainties when extracting A_{CP}, we applied the same cuts, with the exception of Čerenkov identification, to the SCS decays and to the normalizing CF decay for each of the decay modes studied.

To determine the yields for each decay mode, we performed simultaneous binned maximum likelihood fits of the mass distributions (see Figs. 1–5) for the positive and negative candidates. The spectra were fitted with Gaussian signals and linear backgrounds. The widths of the Gaussian functions were constrained to be the same. Reflections from $D^\pm \to K^\mp\pi^\pm\pi^\pm$ appeared near the $D_s^\pm \to K^\mp K^\pm\pi^\pm$ and $K^*(892)K^\pm$ signals, and as a broad shoulder below the $D^\pm \to \pi^\mp\pi^\pm\pi^\pm$ signal. These reflection regions were excluded from the fits.

The mass spectra for all $K^\mp K^\pm\pi^\pm$ combinations that survived the optimized cuts are shown in Fig. 1. The simultaneous fits of the $K^-K^+\pi^+$ and $K^+K^-\pi^-$ mass spectra yielded 1031 ± 44 and 1265 ± 48 signal events for the D^+ and D^-, respectively.

To reconstruct the $D^{\pm}$ in the decay modes $\phi\pi^{\pm}$ with $\phi \to K^+K^-$, we required candidates to have $M(K^+K^-)$ within ± 6 MeV/c^2 of the ϕ mass. Because of the real K^+K^- background under the ϕ signal, we performed ϕ mass sideband subtraction to determine the true number of candidates decaying to $\phi\pi^{\pm}$. The ϕ sideband regions, which were chosen to have summed area equal to the background in the signal region, were $0.990 < M(K^+K^-) < 1.000$ GeV/c^2 and $1.040 < M(K^+K^-) < 1.044$ GeV/c^2. The simultaneous fits of the $\phi\pi^+$ and $\phi\pi^-$ mass spectra, shown in Fig. 2, yielded 474 ± 25 and 598 ± 28 signal events for the D^+ and D^-, respectively.

To reconstruct $D^{\pm} \to K^*(892)K^{\mp}$ with $\overline{K}^*(892)^0 \to K^-\pi^+$ and $K^*(892)^0 \to K^+\pi^-$, we required candidates to have $M(K^{\mp}\pi^{\pm})$ within ± 45 MeV/c^2 of the $K^*(892)$ mass. Here, we also performed $K^*(892)$ mass sideband subtraction to determine the true number of candidates decaying to $K^*(892)K^{\pm}$. The $K^*(892)$ sideband regions were $0.680 < M(K^{\mp}\pi^{\pm}) < 0.750$ GeV/c^2 and $1.040 < M(K^{\mp}\pi^{\pm}) < 1.070$ GeV/c^2. The simultaneous fits of the $\overline{K}^*(892)^0K^+$ and $K^*(892)^0K^-$ mass spectra, shown in Fig. 3, yielded 239 ± 18 and 291 ± 19 signal events for the D^+ and D^-, respectively.

In the study of the decay $D^{\pm} \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$, we investigated possible reflections from $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ and $K^{\mp}K^{\pm}\pi^{\pm}$, and from random combinations of $D^0(\overline{D}^0) \to K^{\mp}\pi^{\pm}$, $\pi^{\mp}\pi^{\pm}$, and $K^{\mp}K^{\pm}$ with a $\pi^{\pm}$. The only significant reflection was from $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$. We excluded this region from the fits, as shown in Fig. 4. The $\pi^-\pi^+\pi^+$ and $\pi^+\pi^-\pi^-$ mass spectra were simultaneously fit using four Gaussian functions for the $D^{\pm}$ and $D_s^{\pm} \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$ signals. The fits yielded 697 ± 42 and 851 ± 48 signal events for the D^+ and D^-, respectively.

We determined the yields of the CF normalizing decay mode $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ that survived the optimized cuts for each of the SCS decays $D^{\pm} \to K^{\mp}K^{\pm}\pi^{\pm}$, $\phi\pi^{\pm}$, $K^*(892)K^{\pm}$, and $\pi^{\mp}\pi^{\pm}\pi^{\pm}$. The simultaneous fits of the $K^-\pi^+\pi^+$ and $K^+\pi^-\pi^-$ mass spectra with cuts optimized for $D^{\pm} \to K^{\mp}K^{\pm}\pi^{\pm}$ are shown in Fig. 5. The fits yielded 23465 ± 183 and 28014 ± 201 signal events for the D^+ and D^-, respectively. Fitting the $K^-\pi^+\pi^+$ and $K^+\pi^-\pi^-$ mass spectra with cuts optimized for $D^{\pm} \to \phi\pi^{\pm}$, $K^*(892)K^{\pm}$, and $\pi^{\mp}\pi^{\pm}\pi^{\pm}$ yielded 31084 ± 254, 23765 ± 182, and 20105 ± 156 signal events for the D^+, respectively.

The signal yields for the D^- were 37057±281, 28384±199, and 23744±169, respectively. We investigated different techniques for extracting the number of D^+ and D^- signal events from the data of Fig. 5, with special attention given to the excess of events seen just below the D mass. In the most extreme case, the ratio of D^+ to D^- increased by 1.9%, which changed the measured asymmetry by 0.9%. This variation is sufficiently small that we neglected it in calculating the 90% confidence level limits.

Using the measured yields of the various decay modes, we have calculated the CP-violation asymmetry parameters A_{CP} directly from Eqs. (3) and (4). The central values have statistical errors of the order of 3–5% and are all consistent with zero asymmetry. These results for A_{CP} and the 90% confidence level limits are summarized in Table I.

As discussed above, in order to extract A_{CP} with no bias, Eq. (2) must be satisfied. Since we are normalizing to the CF decay $D^\pm \to K^\mp\pi^\pm\pi^\pm$, most sources of systematic error cancel. Detector asymmetries may lead to a fake CP asymmetry. However, we expect such effects to be momentum dependent. We investigated any momentum dependence in our efficiencies by comparing the ratio of ratios of the yields of D^+ to D^- for all decays, as they appear in the efficiency relation given above in Eq. (2), in bins of the $D^\pm$ momentum. We also investigated momentum dependence in the asymmetry parameter itself by measuring A_{CP} for the different decay modes in bins of $D^\pm$ momentum. Within our statistical errors, we saw no momentum dependence in either test. Thus, we do not assign any systematic errors for these sources.

Various additional sources of systematic uncertainty were investigated by varying the cuts for the different decay modes, varying the fitting procedure, and performing reflection subtractions instead of excluding the reflection regions from the fits. Variations in A_{CP} were all found to be small compared to the statistical errors and thus were neglected.

In conclusion, we have measured A_{CP} for $D^\pm \to K^\mp K^\pm\pi^\pm$, $\phi\pi^\pm$, $K^*(892)K^\pm$, and $\pi^\mp\pi^\pm\pi^\pm$. We see no evidence of anomalous CP violation in SCS charm decay. The statistical errors on our A_{CP} measurements for the $D^\pm \to K^\mp K^\pm\pi^\pm$, $\phi\pi^\pm$, and $K^*(892)K^\pm$ are more than a factor of two smaller than the only previous measurements [6], and we have made the first measurement of A_{CP} for the decay $D^{\pm} \rightarrow \pi^{\mp}\pi^{\pm}\pi^{\pm}$.

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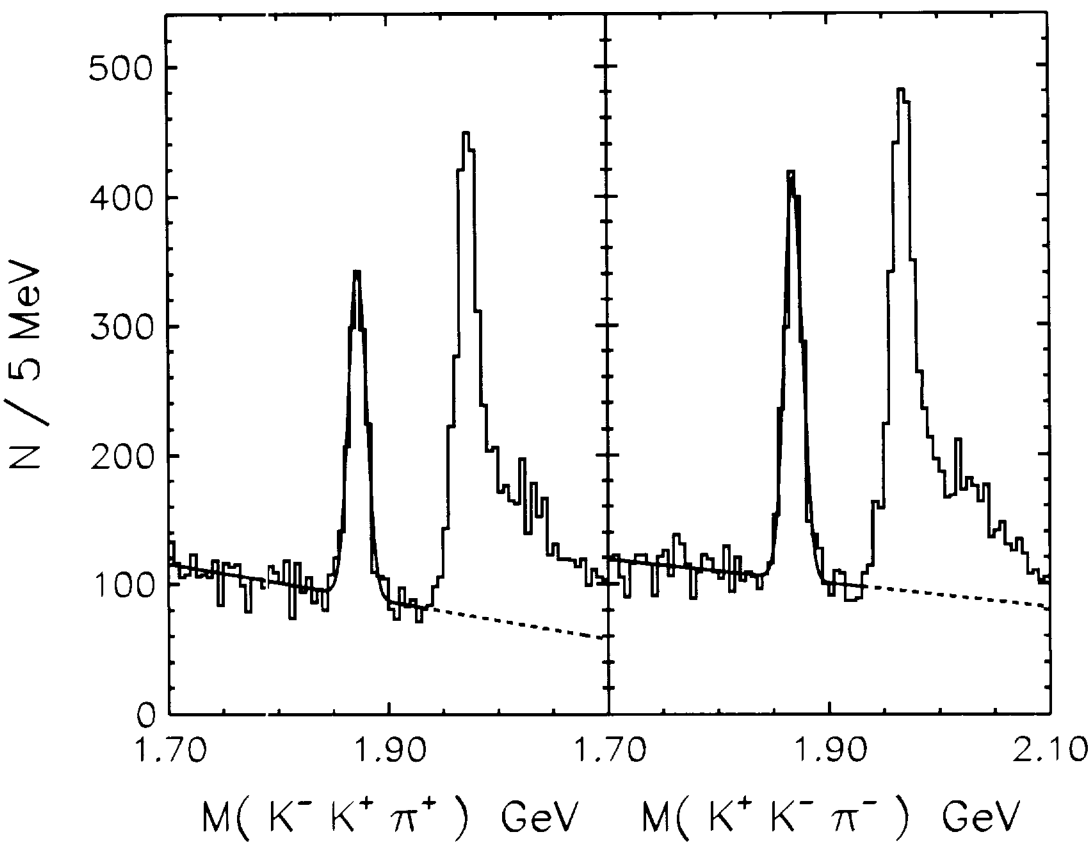

FIG. 1. The fits of $K^-K^+\pi^+$ and $K^+K^-\pi^-$ mass distributions, as described in the text. The $D_s^\pm$ and $K^\mp\pi^\pm\pi^\pm$ reflection region above 1.93 GeV was excluded from both fits. The dashed lines represent the fits extended into the excluded regions.

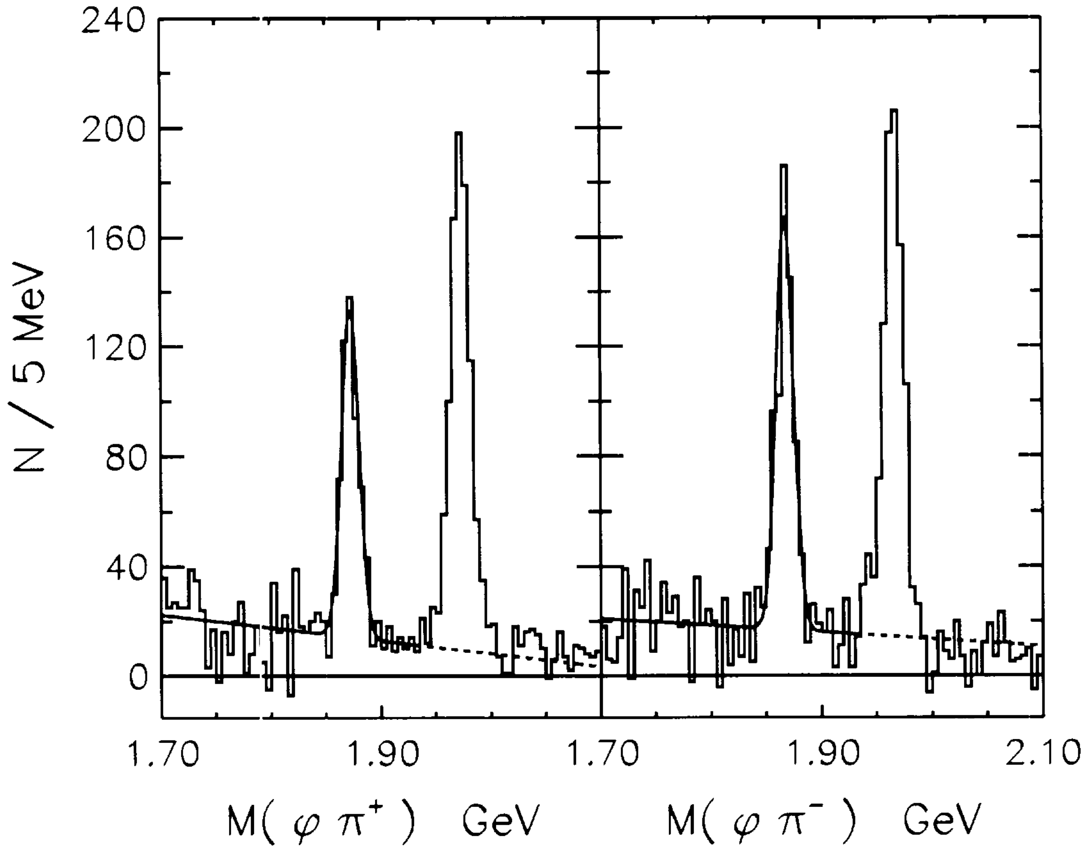

FIG. 2. The fits of $\phi\pi^+$ and $\phi\pi^-$ mass distributions, as described in the text. The $D_s^\pm$ region above 1.93 GeV was excluded from both fits. The dashed lines represent the fits extended into the excluded regions.

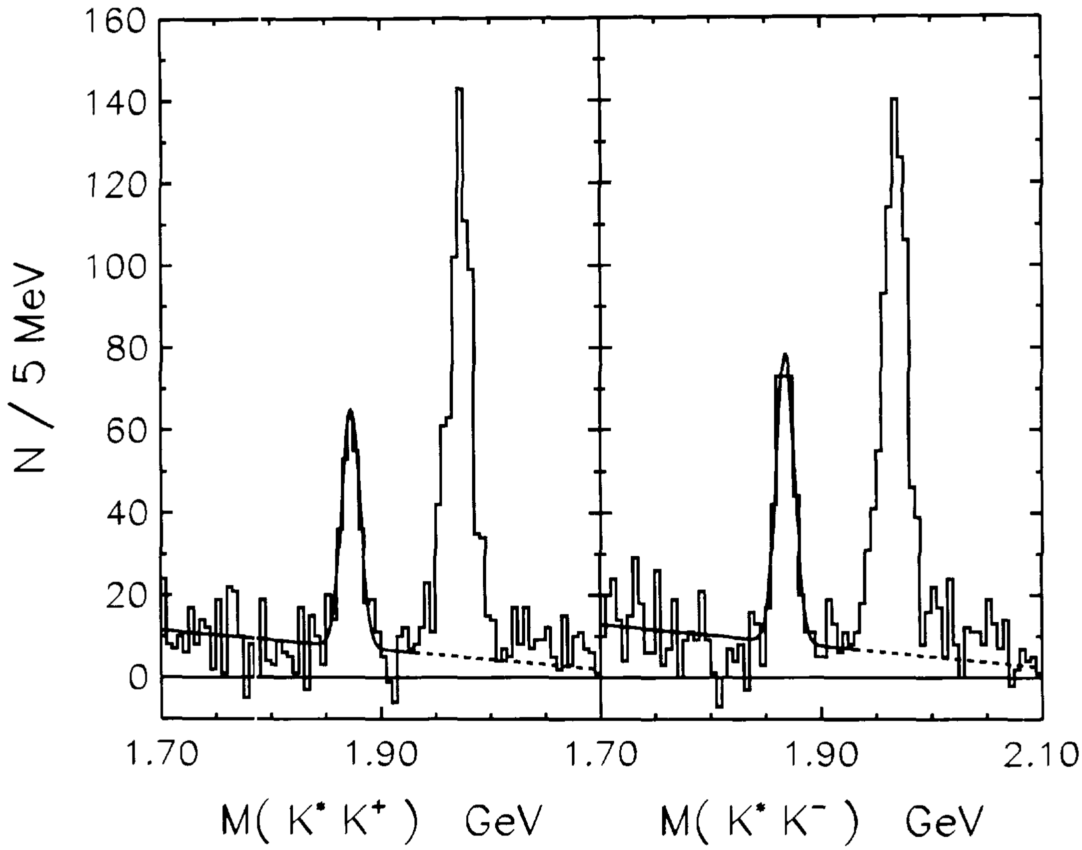

FIG. 3. The fits of $\overline{K}^*(892)^0K^+$ and $K^*(892)^0K^-$ mass distributions, as described in the text. The $D_s^\pm$ and $K^\mp\pi^\pm\pi^\pm$ reflection region above 1.93 GeV was excluded from both fits. The dashed lines represent the fits extended into the excluded regions.

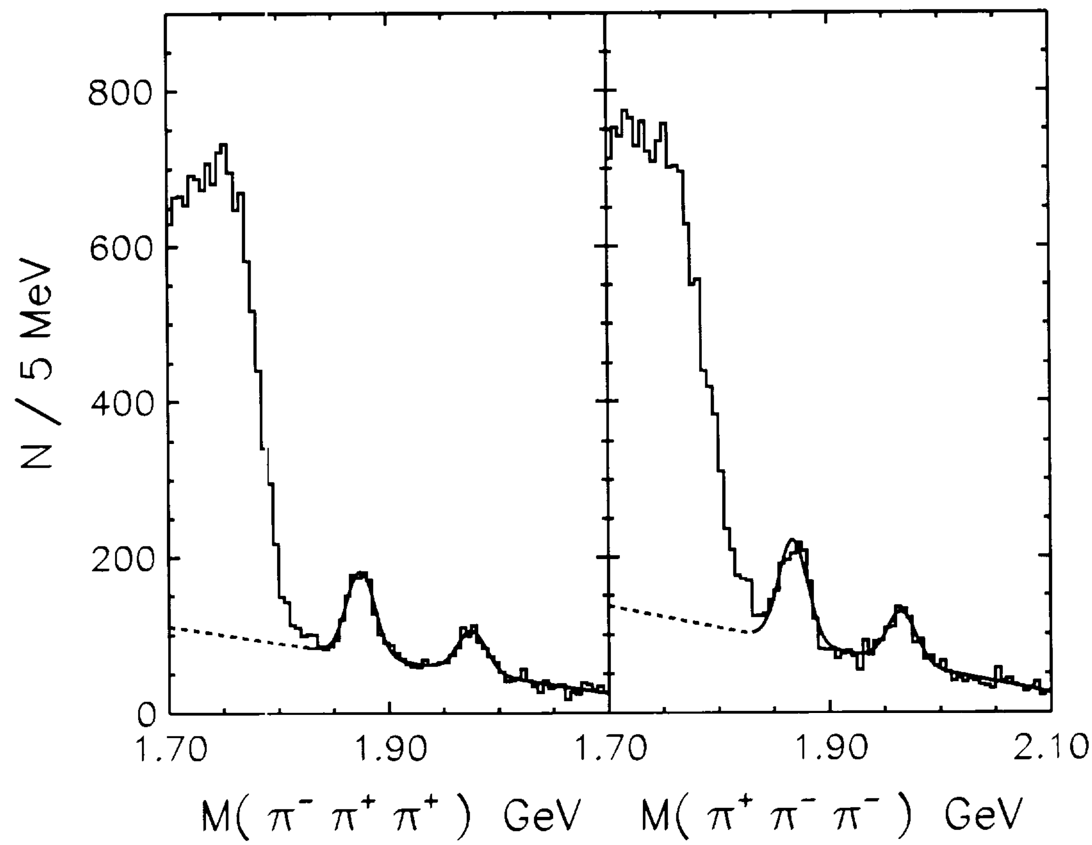

FIG. 4. The fits of $\pi^-\pi^+\pi^+$ and $\pi^+\pi^-\pi^-$ mass distributions, as described in the text. The $K^{\mp}\pi^{\pm}\pi^{\pm}$ reflection region below 1.83 GeV was excluded from both fits. The dashed lines represent the fits extended into the excluded regions.

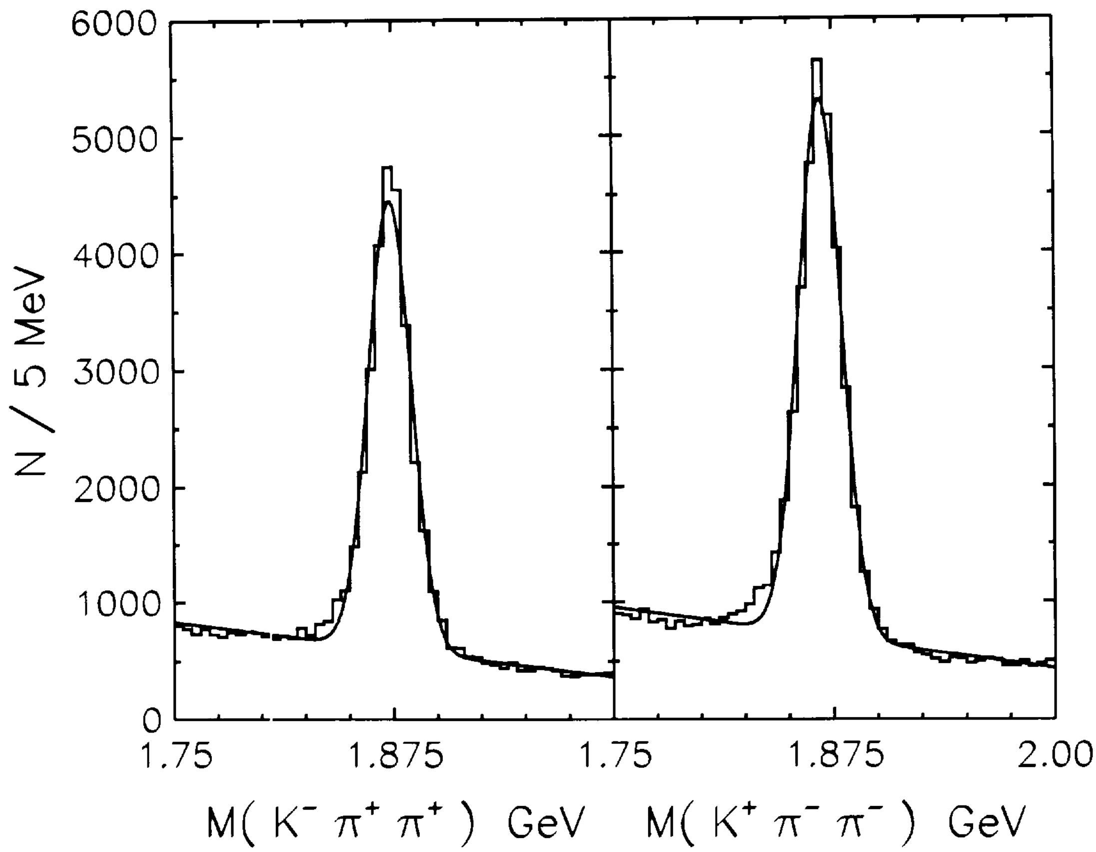

FIG. 5. The fits of the $K^-\pi^+\pi^+$ and $K^+\pi^-\pi^-$ mass distributions for $K^\mp\pi^\pm\pi^\mp$ candidates that survive the $D^\pm \to K^\mp K^\pm\pi^\pm$ selection criteria, as described in the text.

TABLES

TABLE I. Summary of our measured CP-violation asymmetry parameters A_{CP} and the 90% confidence level limits for the singly Cabibbo-suppressed decays $D^+ \to K^-K^+\pi^+$, $\phi\pi^+$, $\overline{K}^*(892)^0K^+$, and $\pi^-\pi^+\pi^+$

Decay Mode	A_{CP}	90% CL Limits (%)
$KK\pi$	-0.014 ± 0.029	$-6.2 < A_{CP} < 3.4$
$\phi\pi$	-0.028 ± 0.036	$-8.7 < A_{CP} < 3.1$
$K^*(892)K$	-0.010 ± 0.050	$-9.2 < A_{CP} < 7.2$
$\pi\pi\pi$	-0.017 ± 0.042	$-8.6 < A_{CP} < 5.2$